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Stereoscopic occlusion and the aperture problem for motion: a new solution [1]

Barton L. Anderson

Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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Abstract

Recent work has shown that the ability of moving contour terminators to determine the perceived motion of untextured contours is strongly constrained by whether contour terminators are classified as *intrinsic* (belonging to a moving contour) or *extrinsic* (belonging to a surface occluding a moving contour). It has also been demonstrated that stereopsis can play a decisive role in this classification. Specifically, Shimojo, Silverman and Nakayama (1989, *Vision Research 29*, 619–626) argued that the efficacy of stereopsis in classifying moving contour terminators as intrinsic or extrinsic stemmed from the relative depth relationships specified by binocular disparity. Here, evidence is presented which demonstrates that the visual system relies on the presence of unpaired contour terminators to classify stereoscopic contour terminators as extrinsic. The author shows that the tendency to perceive untextured contours translating in a single rectangular aperture in a direction parallel to the longer axis of the aperture (the barberpole illusion) was *not* abolished by stereoscopic depth differences when the contour terminators were interocularly paired. However, the illusion *was* abolished when the contours terminators along the longer axis of the aperture were interocularly unpaired. Moreover, contours translated within a square aperture revealed a systematic shift towards the direction of motion signaled by the binocularly paired contour terminators along the horizontal edges of the aperture. These results demonstrate that the classification of stereoscopic contour terminators along an extrinsic–intrinsic dimension results from the presence of local, unpaired contour terminators rather than the relative depth or disparity differences per se, or via the global integration of contour terminators across multiple apertures when multiple apertures are present.

Keywords: Stereoscopic occlusion; Contour terminator; Intrinsic; Extrinsic

1. Introduction

One of the fundamental problems of perceptual organization is understanding how occlusion relationships are identified, so that image regions are correctly partitioned between surfaces at different depths. Rubin (1915) described the computation of occlusion as one of determining the one-sided function of contour, i.e. determining which side of an edge *generated* the contour, and which side of the edge is the background that makes the contour visible. The recovery of occlusion relationships has recently been re-expressed as one of distinguishing between *intrinsic* (occluding) and *extrinsic* (partially occluded) sides of a contour (Nakayama, Shimojo, & Silverman, 1990). In this paper, the role of stereopsis in determining this border ownership assignment is re-examined.

Although there are a number of occlusion cues present in a single monocular image, the visual system has access to new sources of information when recovering occlusion geometry from multiple views (Anderson, 1994; Anderson & Julesz, 1995; Anderson & Sinha, 1997; Nakayama & Shimojo, 1990a,b). For example, stereopsis provides a powerful source of information about relative depth, which can be critical in determining occlusion relationships. Indeed, a recent series of experiments have demonstrated that the intrinsic/extrinsic classification of contours is strongly constrained by stereoscopic information (Anderson & Julesz, 1995; Nakayama & Shimojo, 1990b; Nakayama, Shimojo, & Ramachandran, 1990). One of the most striking exam-

[1] A preliminary version of some of the experiments reported in this paper were presented at the 1994 ARVO conference, Sarasota, Florida.

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ples of the potency of stereopsis in constraining the extrinsic/intrinsic classification was presented in Nakayama, Shimojo and Silverman, (1989). These experiments extended the findings of Wallach (1935)[2], who demonstrated that the perceived motion of translating, untextured contours was constrained by the shape of the aperture through which the contours were viewed. One of the most well known examples from Wallach's work is the barberpole effect: parallel contours translated behind a rectangular aperture appear to move in the direction of the longer sides of the aperture, regardless of their true motion direction. Shimojo et al. (1989) demonstrated that this bias could be effectively eliminated if the contours appeared in stereoscopic depth behind the aperture boundaries. The barberpole effect has been attributed to the propagation of the motion signals generated by the contour terminators along the long sides of the aperture (cf. Hildreth, 1984; Nakayama & Silverman, 1988). Note that the number of terminators along the longer edges of the rectangular aperture are more numerous than those along the shorter axis, so if there is any competition between the motions signaled by the two sets of terminators, the perceived motion should be more strongly constrained by the motion of the terminators along the longer axis of the contour. However, by placing the contours behind the aperture boundaries, Shimojo et al. argued that the contour terminators were classified as extrinsic to the contours since they were generated by the presence of a near, occluding surface, which putatively caused these terminators to be subtracted from the motion integration process.

Thus, Shimojo et al. argued that the classification[3] of the contour terminators as extrinsic was due to the *relative depth* of the moving contours and the aperture edges. This argument makes intuitive sense: since occluding objects must be relatively closer than occluded surfaces, a border shared by a near and far surface must be owned by the near surface. Therefore, if the moving contours are placed behind a shared border, then this border must be extrinsic to the more distant contours. Although this interpretation is consistent with their findings, it is not the only interpretation possible. One of the primary experiments reported by Shimojo et al. employed apertures in which the longer axis was oriented vertically. In this configuration, the disparity difference between the contours and aperture boundaries had two consequences: it introduced a relative disparity between the aperture boundaries and the contours; and it generated *unpaired contour terminators* along the elongated, vertical axis of the aperture (see Fig. 2). We have recently demonstrated that occlusion geometry can generate horizontal and vertical displacements of the image junctions formed by the interruption of a contour by an occluding surface (Anderson, 1994; Anderson & Julesz, 1995). Our work demonstrated that local shifts in the interocular positions of contour terminators provides information about the presence of an occluding surface by generating local vertical displacements of the contour junctions. These local, vertical shifts putatively provide information that the contour terminators correspond to partially occluded surface regions, and are therefore interocularly unpaired. Indeed, these unmatched contour segments can give rise to vivid percepts of illusory occluding contours (where illusory refers to the absence of visible contrast along the occluding contour; see Anderson, 1994; Anderson & Julesz, 1995). This suggests the possibility that the classification of the contour terminators as extrinsic in the study by Shimojo et al. (1989) was due to the fact that the contour terminators along the longer (vertical) axis were interocularly unpaired (half-occluded), rather than being caused by the depth difference per se. In the experiments reported by Shimojo et al., these two properties covaried, and hence, it is impossible to determine the relative contributions of these two factors in the classification of the contour terminators as extrinsic.

In order to experimentally distinguish between these two alternative explanations, the effects of relative depth must be dissociated from the effects of unpaired contour terminators. We have previously shown that unpaired contour terminators will be generated by all surfaces except for those that are horizontal relative to the line of sight (Anderson, 1994; Anderson & Julesz, 1995). The intuitive basis of this geometric fact can be understood by recognizing that unmatchable features are generated when an occluding surface allows one eye to see around the occluding edge more than the other, which occurs whenever the occluding contour has some degree of vertical inclination relative to an observer's line of sight. A perceptual consequence of this geometric principle can be observed directly in Fig. 1. In the top figure, a series of contours oriented at 45 degrees was given a disparity that caused them to appear behind a vertically (Fig. 1a) and horizontally (Fig. 1b) oriented aperture. A striking perceptual difference between these two displays can be observed: Vivid illusory contours are generated along the vertical sides of both displays, but not along the horizontal aperture edges. Note, however, that for the vertically oriented aperture, the illusory contours form alongside the *longer* axis of the aperture, whereas the horizontally oriented apertures generate illusory contours alongside their *shorter*

[2] An English translation of Wallach's seminal work was recently published by Wuerger, Shapley and Rubin (1996).

[3] The term *classification* was introduced by Shimojo et al. and is retained herein soley for the purpose of terminological consistency. Indeed, our data suggest that the terms intrinsic and extrinsic correspond to endpoints on a continuous scale, not a rigid dichotomy.

(a)

(b)

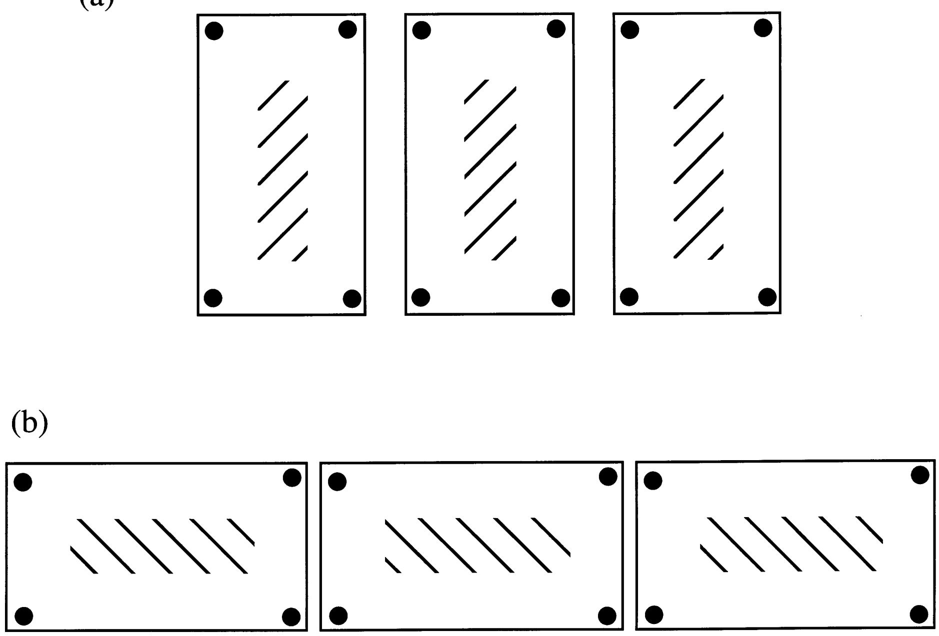

Fig. 1. Stereograms demonstrating the difference between horizontal and vertical apertures in the generation of unpaired contour terminators. The 45 degree contours were shifted horizontally behind an invisible vertical (top) or horizontal (bottom) aperture. This horizontal shift generates a vertical displacement of the contour terminators along the vertical aperture boundaries, but not the horizontal boundaries. These unpaired terminators generate illusory contours along the longer axis of the aperture in (a), and along the shorter axis of the aperture in (b) (cross fusers should fuse the left two stereograms, divergent fusers should fuse the right two stereograms).

axis. In other words, for vertically oriented apertures, the unpaired terminators arise along the side of the aperture that would normally determine the perceived motion direction of the contours, whereas in horizontally oriented apertures, the unpaired terminators arise along the side of the aperture that are thought to be discounted (or weighted less) in the motion integration process.

The difference between the horizontal and vertical aperture orientations allows us to determine the contributions of relative depth and unpairable features in explaining the influence of stereoscopic depth on the barberpole effect. If unmatchable features play a role in classifying a contour terminator as extrinsic, then contours moving in vertically oriented apertures should be effected less by the terminators along the longer side of the aperture than contours presented in horizontally oriented apertures. But if the classification of a terminator as extrinsic depends primarily on relative depth, then there should be no difference in the role of stereoscopic depth in determining the perceived motion direction in horizontal or vertical apertures. Experiment 1 was performed to test for the presence of anisotropies in the effects of aperture orientation and disparity on the barberpole effect.

2. Experiment 1: asymmetries in the influence of stereoscopic depth on horizontal and vertical apertures

2.1. Method

The two displays depicted in Fig. 2 were used as the stimuli for Experiment 1. The pattern contained a binocular square wave pattern of alternating white and black stripes oriented at 45 degree relative to horizontal. One half-cycle subtended 3.15 arc min of visual angle. The stripes were embedded in horizontal and vertical apertures, and the displays were viewed binocularly by means of a haploscope. One of five different values of disparity was assigned to the stripes, such that they would appear either in front, behind, or at the same depth as the aperture boundary (7.8, 3.9, 0, − 3.9, − 7.8 arc min disparity, respectively). Negative values therefore indicate that the contours appear farther than the aperture boundary, and positive values indicate that the aperture boundary is behind the moving contours. The apertures had an aspect ratio of 2:1, subtending 1.3 and 0.65°, respectively. The stripes were translated in a rightward direction, and the component of motion orthogonal to the contours' orientation had a constant value of 1.58 deg/s.

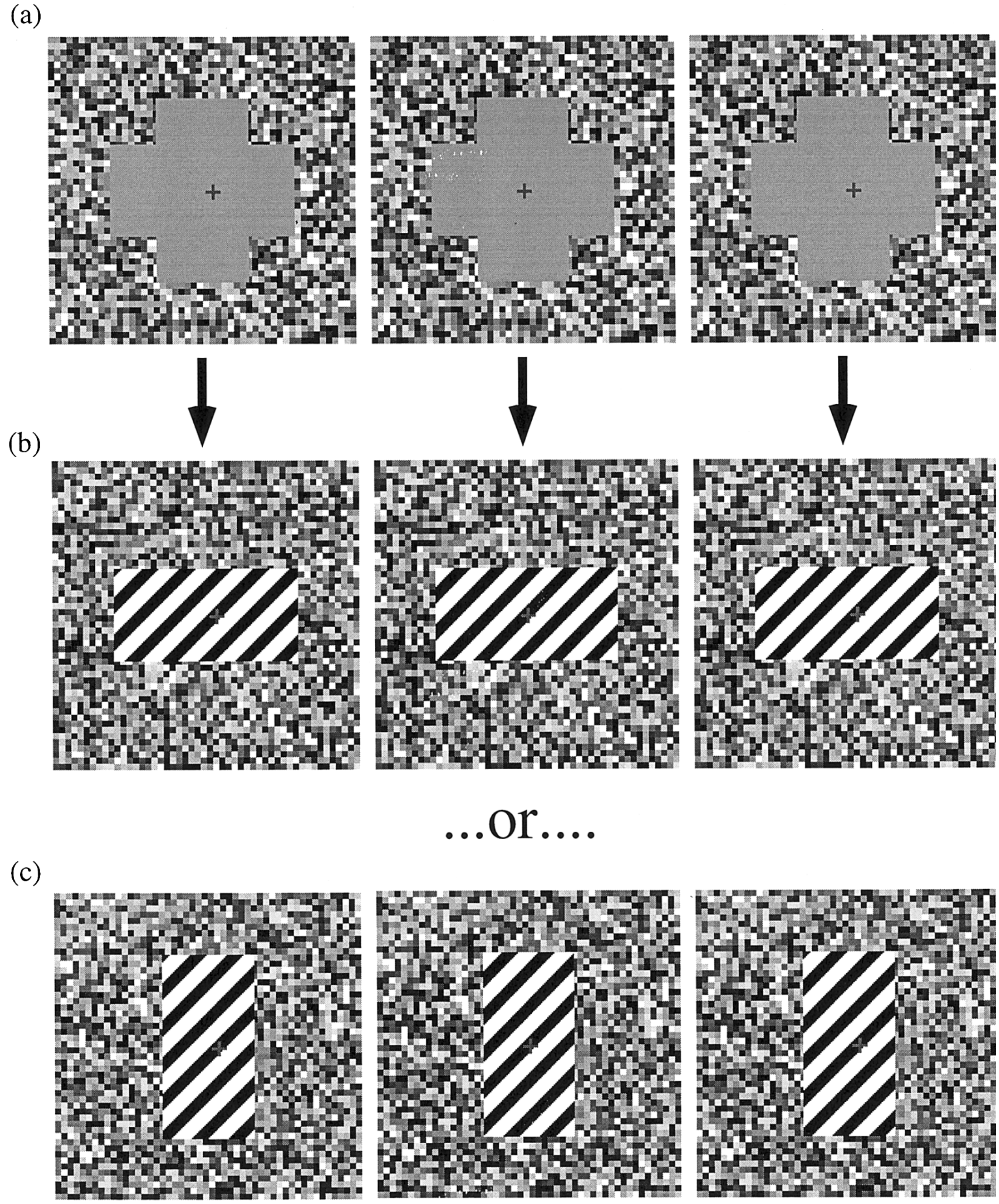

Fig. 2. The stimulus and method used in Experiment 1. A series of contours oriented at 45 degrees relative to horizontal were translated to the right behind vertical and horizontal apertures. (a) A single trial began with a fixation pattern that contained a fixation cross at the depth that the stripes. The press of a computer mouse initiated a motion sequence of stripes translated within either horizontal (b) or vertical (c) stripes, varied randomly from trial to trial. Observers would then adjust the orientation of a small contour segment to match the perceived motion direction of the contours within the aperture.

The motion display was preceded by the fixation stimulus presented in Fig. 2. This display contained a zero disparity random-dot background, overlaid with horizontal and vertical rectangles that were uniformly colored with a grey corresponding to the mean luminance of the random-dot pattern. A small, red binocular fixation cross was presented in the center of the displays at the depth that the stripes would appear for a given block of trials. A trial began when the subject clicked the mouse, which initiated the motion sequence. The motion sequence was presented for a total of 0.76 s, and the refresh rate of the monitor was 75 Hz. The motion sequence was immediately followed by the original fixation pattern, and the subject was then required to report the perceived direction of the contours' motion by adjusting the orientation of a small contour segment so that it matched the perceived motion direction.

2.1.1. Observers

Three observers with normal or corrected to normal vision served as experimental subjects, two of which were naive to the purposes of the experiment.

2.1.2. Procedure

Observers performed a series of five blocks of trials, corresponding to the five different disparity values (7.8, 3.9, 0, -3.9, -7.8 arc min), in a pseudo-random order. Each block contained 60 trials, 30 for horizontally oriented apertures, and 30 for vertically oriented apertures. Within a block of trials, the aperture orientation was varied randomly between horizontal and vertical. Trial presentation was self paced, but intrinsically limited by the time it took observers to adjust the orientation of the small line segment to match the perceived motion direction. Subjects were instructed to perform at a moderately slow rate to reduce hysteresis effects.

3. Results

The results for the three subjects are presented in Fig. 3. The abscissa represents the relative disparity between the aperture boundary and the stripes of the barberpole; positive numbers correspond to the condition in which the stripes were in front of the aperture boundary, and negative numbers correspond to the condition in which the stripes were behind the aperture boundary. In order to directly compare the horizontal and vertical aperture orientations, the orientation judgements of the subjects were normalized such that the longer axis of the rectangular aperture was treated as an orientation judgment of zero degrees. Thus, for vertically oriented apertures, a response of 0 degrees corresponds to a percept of the stripes moving downward, and a response of 45 degrees corresponds to a percept of the stripes moving down and to the right. For horizontally oriented apertures, a response of 0 degrees corresponds to a percept of the stripes moving rightward, and a response of 45 degrees again corresponded to a percept of the stripes moving down to the right. Thus, for both vertically and horizontally oriented apertures, 0 degree responses correspond to a percept of the classic barberpole illusion (hereafter referred to as barberpole motion), and 45 degrees corresponds to a percept of contours moving orthogonally to the contour's orientation.

These data reveal strong effects of both aperture orientation and stereoscopic depth on the perceived motion direction of the contours. Pairwise t-tests were performed between five of the conditions, adjusted so that the family-wise alpha level did not exceed 05. When the contours and the aperture boundary appeared at the same depth, there was a strong bias to perceive barberpole motion for both horizontal and vertically oriented apertures. There was a smaller but statistically reliable bias to perceive barberpole motion in the zero depth difference condition when the orientation of the aperture was horizontal rather than vertical ($P \ll 0.01$). However, the manipulation of stereoscopic depth had a very different effect on perceived motion direction presented within horizontal versus vertical apertures. For vertically oriented apertures, the manipulation of stereoscopic depth caused a strong release from barberpole motion when compared to the zero disparity case, which increased significantly with the magnitude of the disparity ($P < 0.001$). Although this effect was strongest when the stripes appeared behind the aperture boundary, there was also significant tendency for the stripes to appear to move in a direction orthogonal to their orientation when the stripes appeared in *front* of the aperture boundary ($P \ll 0.01$). However, unlike the disparity dependence of the far condition, there were no statistically reliable differences observed between the two near disparity values. An ANOVA revealed that the manipulation of stereoscopic depth had no effect on the perceived motion direction when the stripes that were translated within horizontal apertures ($P = 0.36$).

4. Discussion

The results of Experiment 1 demonstrate that the release from barberpole motion elicited by the manipulation of stereoscopic depth occurs for vertically oriented apertures, but is *not* observed when observers view stripes moving within a single horizontal aperture. The relative depth differences between these two patterns were identical, so depth per se can not provide an account of the different pattern of results for horizontal and vertical apertures. Moreover, whereas Shimojo et al. (1989) found that a release from barberpole motion only occurred when the moving stripes appeared behind the vertical aperture, we found that there was also a release from barberpole motion when the stripes appeared in *front* of the vertical aperture, albeit to a smaller degree than when the stripes appeared behind the aperture.

Our account of both our and Shimojo et al.'s results relies on presence and absence of unmatchable contour terminators. When stereoscopic depth differences are introduced between the aperture boundary and the moving stripes, unmatchable contour terminators are generated along the vertical contours (or more generally, any contour that has some component of vertical inclination relative to an observer's line of sight). For vertically oriented apertures, these unpaired contour terminators arise along the longer axes of the aperture. In contrast, the unpaired contour terminators arise

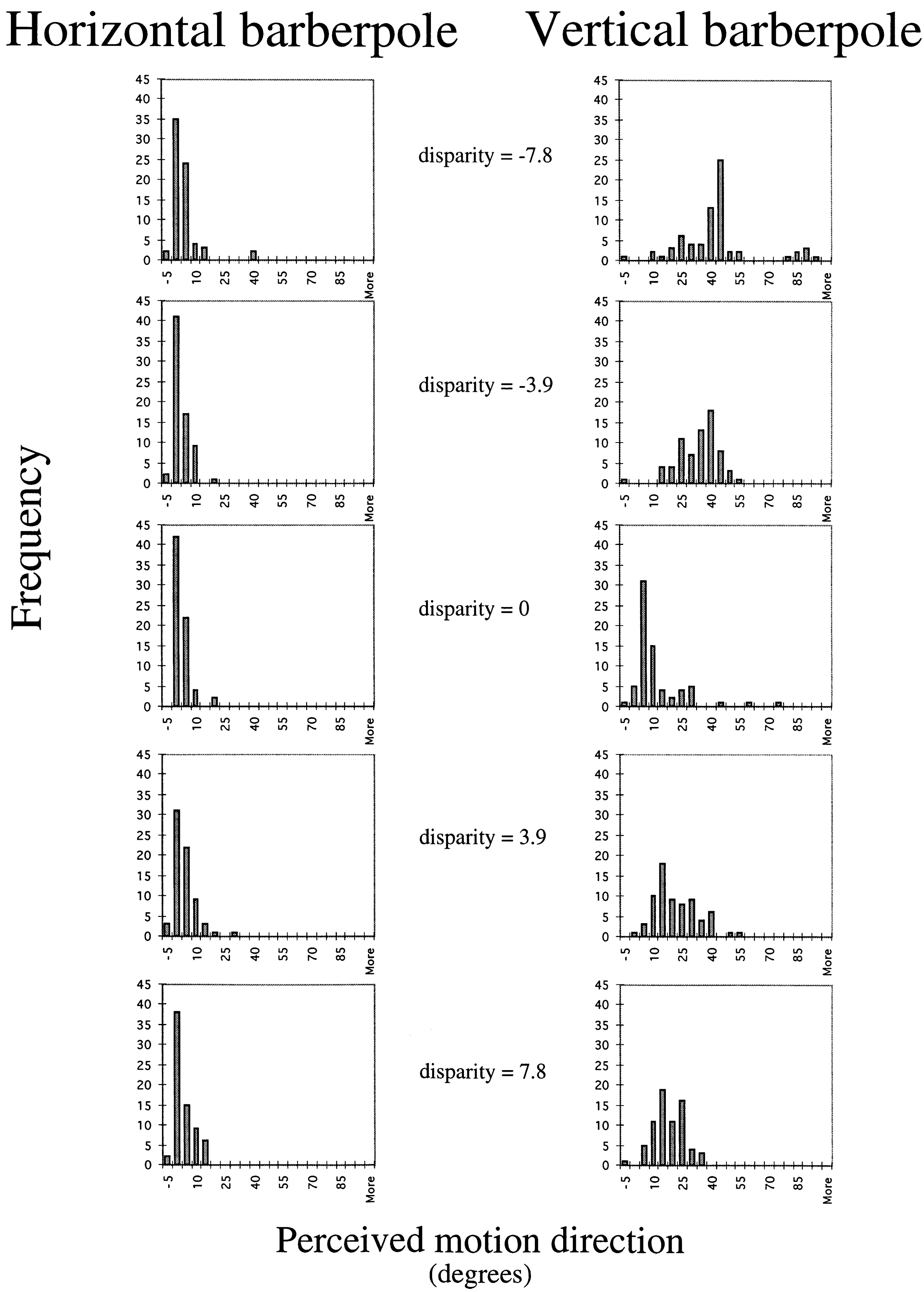
Horizontal barberpole
Vertical barberpole
Frequency
disparity = -7.8
disparity = -3.9
disparity = 0
disparity = 3.9
disparity = 7.8
Perceived motion direction
(degrees)

Fig. 3.

along the *shorter* aperture axes for horizontally oriented apertures. If the classification of contour terminators as extrinsic relied on the contours being *unpaired*, then the manipulation of stereoscopic depth should generate a strong difference between vertically and horizontally oriented contours: Vertically oriented apertures should exhibit a much stronger release from barberpole motion than horizontally oriented apertures, which is exactly what we found. Indeed, we found no evidence for a release from barberpole motion for contours translated in horizonal apertures.

In addition to correctly predicting the asymmetry between horizontal and vertical apertures, the thesis that the intrinsic/extrinsic classification relies on terminators being paired or unpaired also correctly predicts that there should also be a release from barberpole motion when the moving contours appear in front of the aperture boundary, since both depth conditions generate unpaired contour terminators (Anderson & Julesz, 1995). Indeed, the only difference between the images in the near and far disparity conditions is that the two eye's views have been interchanged (which inverts the relative disparities), which means that the unpaired terminators must be present in both cases. Although there is no globally consistent surface interpretation when the stripes appear in front of the aperture boundary[4], the fact that observers experienced a release from the barberpole illusion in these conditions suggests that the visual system utilizes unpaired features to classify local contour terminators as extrinsic.

The preceding discussion treats the concept of unpaired terminators as though it were a property of images. Clearly, however, the classification of a feature as unpaired is a consequence of visual processing; it is not a property of images per se. We (Anderson, 1994; Anderson & Julesz, 1995) have previously demonstrated that the geometry of occlusion introduces vertical shifts at occlusion junctions, and have argued that the visual system treats these local, vertical shifts as stereoscopically unmatchable. Note, however, that such vertical shifts are *not* generated if one of the two contours forming the occlusion junction is oriented horizontally relative to the line of sight. Thus, the claim that unpaired terminators are not present along horizontal contours is based on a geometric principle coupled with an assumption that the visual system treats local vertical shifts of contour junctions as unmatchable (here, the relevant contour junctions are those formed by the intersection of the lines of the barberpole pattern with the edges of the aperture). Note that the vertical shifts that arise at occluding contour junctions are not vertical *disparities*, since they arise from the projection of *different regions* of environmental surfaces onto the two eyes. Moreover, whereas vertical disparities must be present over large portions of the visual field in order to influence stereoscopic depth (Rogers & Bradshaw, 1993), the vertical shifts arising at occlusion junctions can elicit subjective occluding contours for even a single, vertically displaced contour (Anderson, 1994; Anderson & Julesz, 1995).

In sum, the current data suggests that the intrinsic/extrinsic classification of contour terminators relies heavily on whether the terminators are matched or unmatched. However, to this point, this argument has relied on the large difference between the effects of binocular disparity on contours moving within vertical versus horizontal apertures. One potential problem with this interpretation is that the responses for the horizontally oriented apertures are all clustered around the major axis of the aperture, i.e. virtually all of the responses are horizontal (barberpole) motion. It is possible, then, that the difference between the horizontal and vertical apertures was due to a floor effect wherein observers simply always responded horizontal to the contours that moved within the horizontal apertures. This may simply reflect a stronger *monocular* bias for the perception of horizontal motion, which may have simply masked any effects that disparity might have had on the horizontal apertures (cf. Mulligan, 1992; Shapley & Rubin, 1996). In order to conclusively demonstrate that the classification of a stereoscopic contour as extrinsic relies on the terminator being unpaired, we must demonstrate that unpaired contour terminators have a different effect on perceived motion

[4] If the stripes are replaced with random-dots that have the same disparity values as the stripes, the unpaired features would be seen at the same depth as the random-dot background when the dots within the aperture were given a near disparity. A similar percept can be experienced when the stripes appear in front of the aperture: the unpaired terminators do not appear in front with the central region of the stripes, but rather, appear at the depth of the random-dot background. Thus, the terminators are not even perceived at the same depth as the contours, and consequently, must be extrinsic to the contour.

Fig. 3. Histograms of the data from Experiment 1. The left column depicts the perceived direction of motion within horizontal apertures, and the right column depicts perceived motion direction within vertical apertures. Each row represents a single disparity difference between the random-dot background and the moving contours. Negative disparity values indicate that the moving stripes appeared behind the background (disparity is in units of arc min). The data has been normalized so that zero degrees corresponds to motion along the longer axis of the aperture, and 45 degrees corresponds to motion orthogonal to the orientation of the contour. The introduction of stereoscopic depth had a large impact on the perceived motion direction when it generated unpaired contour terminators along the longer axis of the barberpole (vertically oriented apertures), but no statistically detectable effect was observed when unpaired terminators were not generated along the longer axis of the aperture (horizontally oriented apertures). Note that a release from barberpole motion was observed for contours that appeared behind and in front of the aperture boundaries.

direction than paired terminators in displays that are not always perceived in a single direction of motion, and in which depth is not confounded with the paired/unpaired distinction. This was the purpose of Experiment 2.

5. Experiment 2: perceived motion of contours within square apertures depends on relative depth

The main thesis described above is that the classification of a stereo contour terminator as extrinsic relies more on whether it is binocularly unpaired, than on the depth of the contour. In Experiment 1, we tested this thesis by viewing contours moving behind rectangular apertures. However, if this thesis is correct, then we should be able to see the differential effects of paired versus unpaired contour terminators when viewing contours moving within *square* apertures formed by vertical and horizontal contours. The logic of this experiment is straightforward. The presence of stereoscopic depth will introduce unpaired terminators along the two vertical boundaries, but not along the horizontal contours. Thus, if the unpaired contour terminators are used to classify a contour as extrinsic, then the introduction of stereoscopic depth should cause a systematic shift towards an increased number of horizontal responses. However, if there is simply a monocular bias to perceive horizontal motion then the manipulation of disparity should have no effect on the perceived direction of motion of the contours; there should simply be a consistent bias to perceive horizonal motion, independently of the stereo depth relationships in the images. Note that the depth thesis of Shimojo et al. also predicts that depth should have no impact on these displays.

5.1. Methods

5.1.1. Stimuli and procedure

The stimuli and procedure of this experiment are identical to that of Experiment 1, except that a single square aperture (0.65×0.65 arc min) replaced the two rectangular apertures (see Fig. 4). The fixation pattern contained a single, untextured square with a luminance that matched the random-dot pattern's mean luminance.

5.1.2. Observers

Two new observers with normal or corrected to normal vision served as subjects. Both were naive as to the purpose of the experiment.

5.2. Results

The raw data of this experiment for the two observers are presented in Fig. 4 (a), and the means are presented in Fig. 4 (b). In both figures, a response of zero degrees indicates horizontal motion, and a response of 45 degrees indicates motion orthogonal to the contours. As predicted, stereoscopic depth differences between the aperture boundary and the moving stripes caused a statistically reliable bias toward horizontal motion for both observers (as before, data were analyzed with pairwise t-tests adjusted so the family-wise alpha level was less than 0.05). When no stereoscopic depth differences are present, both observers report that a larger proportion of the displays appeared to translate in a direction orthogonal to the contour's orientation (45 degrees). Note that neither subject reported downward motion in any condition (90 degrees), although both subjects generated horizontal responses in all depth conditions. Although the data demonstrate the presence of a monocular bias to perceive horizontal motion, there is a substantial and statistically reliable increase in the tendency to perceive horizontal motion when the contours appear behind *and* in front of the aperture boundaries (when compared to the zero disparity condition). Pairwise t-tests revealed that this bias increases significantly with an increase in the magnitude of the disparity for both the near and far conditions ($P \ll 0.01$). A monocular bias to see horizontal motion therefore cannot account for the increased number of horizontal responses when the aperture boundary and the stripes are at different depths, since this bias should not generate any differential effects of relative depth. These conditions are exactly those that generate unpaired contour terminators along the vertical edges of the aperture boundary.

The results of Experiment 2 demonstrate that the difference between horizontal and vertical apertures described in Experiment 1 cannot be simply attributed to a differential monocular bias in perceiving horizontal versus vertical motion. Taken together, these two experiments provide compelling evidence that the classification of stereoscopic contour terminators as extrinsic critically depends on whether the terminators are binocular unpaired, rather than just the relative depth of the contour segments.

6. General discussion

The results of the preceding experiments provide a different understanding of how the visual system uses stereoscopic information to classify contour terminators as extrinsic or intrinsic. Whereas Shimojo et al. have previously argued that the classification of contour terminators as extrinsic required that the contours appear partially occluded, our results show that this particular depth relationship is neither necessary or sufficient for an extrinsic classification of a local contour terminator. With regard to necessity, the preceding

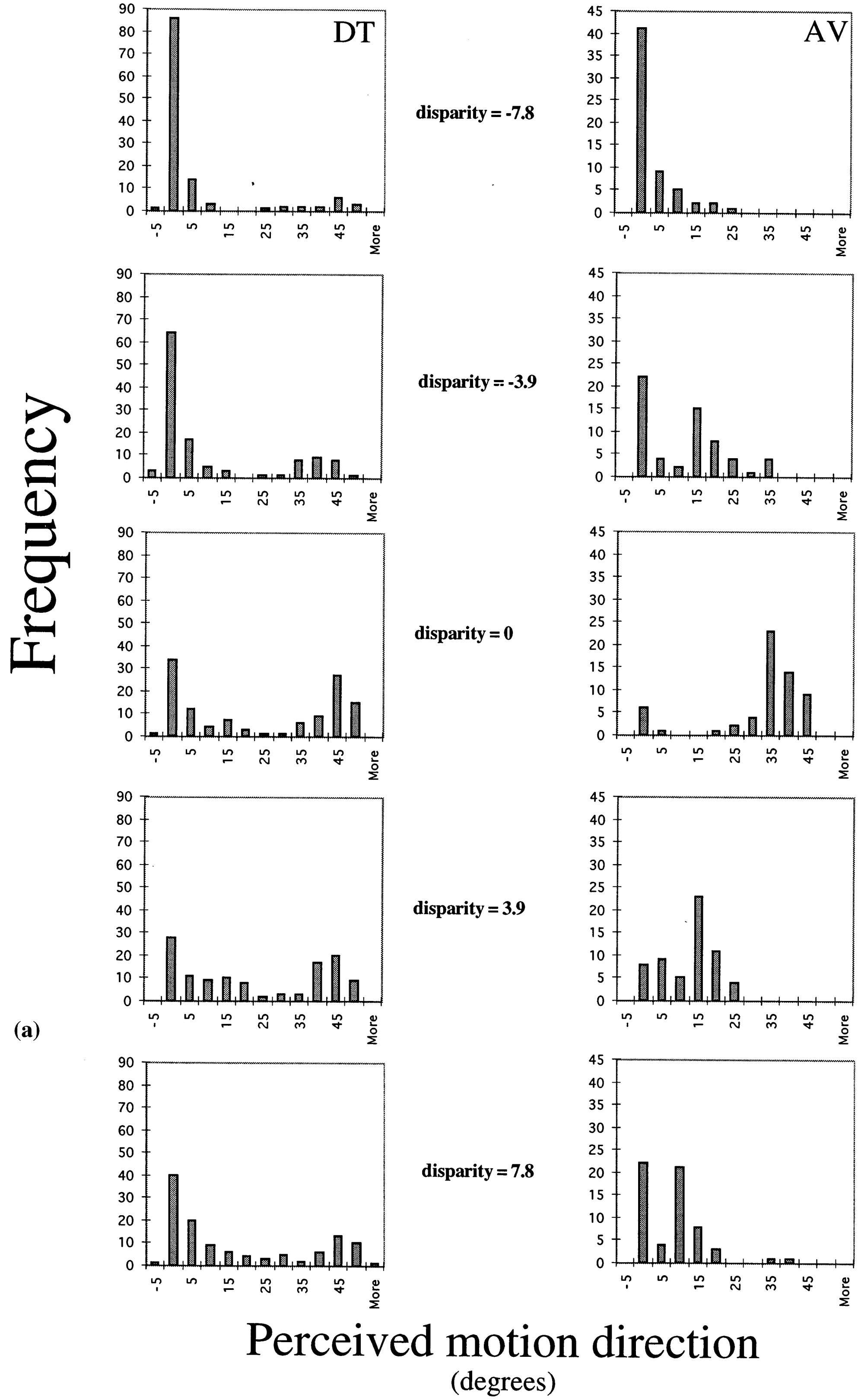

Fig. 4. (a) Histograms of the data for the two naive observers when contours were translated behind the square apertures used in Experiment 2. Both observers reveal a statistically reliable increase towards horizontal motion for when the contours appeared behind (top of figure) or in front (bottom of figure) of the random-dot background. (b) Average data of the two subjects plotted with 95% confidence intervals. The data reveal a systematic, depth dependent bias towards horizontal motion for both directions of disparity. See text for details.

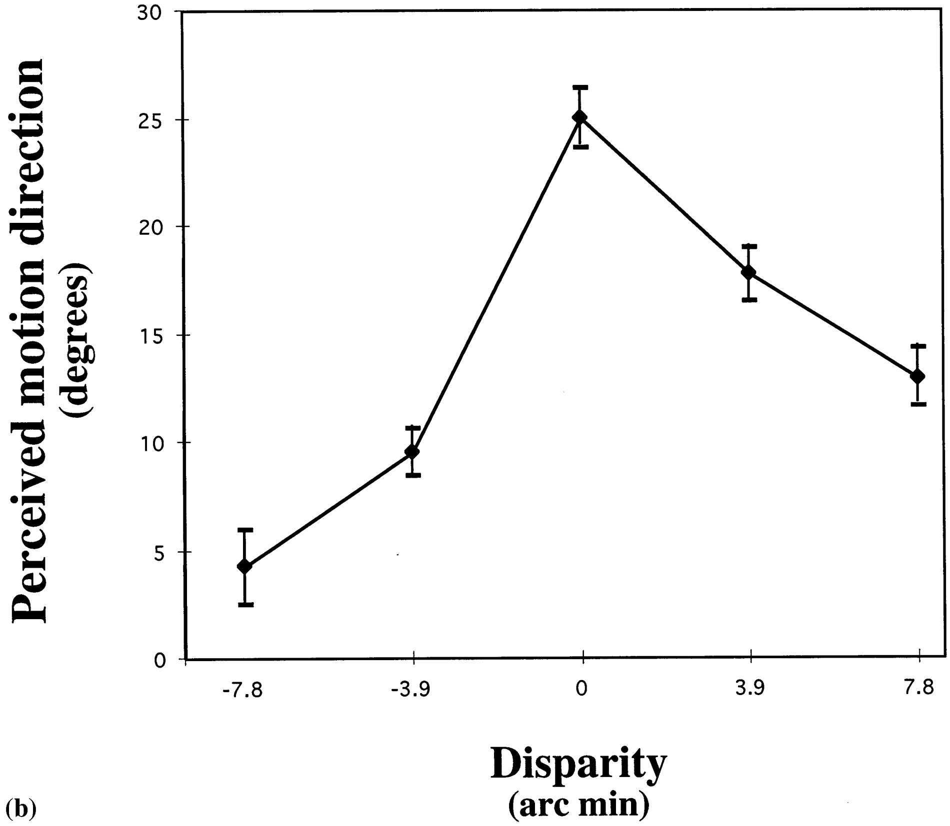

Fig. 4. (*Continued*)

experiments demonstrate that a release from the barberpole illusion occurs when the contours appeared in *front* of the aperture boundaries, as well as when the contours appeared behind and partially occluded by the aperture boundaries. Therefore, the perception of an aperture boundary as an occluding surface is not necessary for a release from the barberpole illusion. Although it is impossible to determine why the results reported here are different than those reported by Shimojo et al., there were both methodological factors and stimulus differences that might account for the different results. The most likely cause of the difference between the two studies was the aspect ratio of the apertures that were used. Shimojo et al. study used aperture ratios of 1:2.75, whereas that used here was 1:2. This means that the barberpole motion should have been more dominant in the Shimojo et al. study, which may have obscured the (weaker) release from barberpole motion that occurred when the stripes appeared in front of the aperture boundaries, while leaving the relatively stronger release observed in the stripes behind condition intact. Indeed, our pilot work revealed results similar to those of Shimojo et al. when an aspect ratio of about 1:3 was used.

In addition to the difference in stimuli, the methods used in the two studies were also different. Observers in Shimojo et al.'s study were forced to simply categorize a motion as either predominantly horizontal or vertical on a given trial. In the experiments reported here, observers were required to report a specific angle of the perceived motion direction on each trial (see also Rubin & Hochstein, 1993). Thus, even if the observers in the Shimojo et al. study exhibited a systematic deviation away from barberpole motion when the moving contours were in front of the aperture boundaries, observers would only report such deviations when the contours appeared to move *predominantly* horizontal (i.e. in the direction orthogonal to the elongated axis of the aperture). Their method would not detect a deviation away from the barberpole illusion that was less than 45 degrees, and hence, their method was less sensitive than the method used here[5]. It therefore seems likely that the difference between the results reported here and those reported by Shimojo et al. may be due to a difference in the sensitivity of our data collection procedure, as well as differences in the stimuli chosen.

With regard to the sufficiency of depth in predicting a release from barberpole motion, the author has shown that the addition of occlusion appropriate depth

[5] It is worth noting, however, that the data for one of the four subjects in Shimojo et al.'s study revealed a significant departure from barberpole motion when the stripes appeared in front of the aperture. However, no theoretical significance was attributed to this fact in their paper.

differences did not cause a release from barberpole motion in horizontal apertures, even though the depth relationships of the aperture and the contours were consistent with occlusion. Although stereoscopic depth must be present to generate unpaired features, the presence of occlusion consistent depth relationships is not sufficient for an extrinsic classification of the contour terminators, at least in these single aperture displays. Although the horizontal/vertical anisotropy might have been due to a monocular bias to perceive horizontal motion, Experiment 2 showed that contours moving within a square aperture also exhibited a depth dependent shift towards horizontal motion when the contours appeared either in front or behind the aperture boundary. In these conditions, the contour terminators along the vertical sides of the aperture were unpaired, whereas those along the horizontal aperture boundaries were not. If the classification of stereoscopic contour terminator as extrinsic relied on the presence of unpaired contour terminators, then the shift toward horizontal motion is expected, and these results can be readily understood.

One of the more surprising results reported here is the release from barberpole motion when the moving contours appeared in front of the aperture boundaries. Although the release from the barberpole illusion was greater for the occlusion appropriate (top of Figs. 3 and 4) than for the occlusion inappropriate conditions (bottom of Figs. 3 and 4), there was a clear difference in the perceived motion directions of the contours when they appeared as the same depth as the background, and when the contours appeared in front of the aperture boundaries. This fact implies that there must be some mechanisms that sense whether a binocular contour segment contains a paired or unpaired terminator, and uses this fact to classify the terminator as intrinsic or extrinsic (at least as a crude initial estimate). However, neither the unpaired thesis or Shimojo et al.'s depth explanation of terminator classification can provide a full account of the pattern of results reported. As mentioned above, Shimojo et al.'s explanation cannot explain the horizontal/vertical aperture asymmetry, and the unpaired thesis cannot explain the difference in the *extent* of the release from barberpole motion in the near and far depth conditions (since both the near and far contain unpaired terminators). What, then, is needed to provide a coherent account of all of these results?

The most natural way to understand the different results reported both here and previously is to assume that more than one process is involved in classifying contour terminators along the extrinsic/intrinsic dimension. The data presented above strongly suggest that the classification of terminators relies on the presence or absence of unpaired contour segments. However, the occlusion appropriate configuration was more effective at causing a release from the barberpole illusion, which suggests that there must be some additional (or at least different) processing that takes into account the global consistency of the viewing geometry. Indeed, there is some evidence that more global processes responsible for integrating fragments motion signals into a single object play a role in the classification of moving terminators. Shimojo et al. (1989) reported that the perception of motion in three horizontal apertures would appear to shift towards vertical motion if the apertures could be interpreted as a single, amodally completed vertical aperture occluded by two horizontal surfaces. We performed similar experiments and found similar effects. It therefore seems likely that there is more than one kind of process that is influencing the classification of contour terminators and perceived motion direction in these displays (see also McDermott, Weiss, & Adelson, 1998). For contours moving within a single, isolated contour, the intrinsic/extrinsic classification must rely on relatively local cues, since no other source of information is available on which to base a classification. However, there also seems to be a second process that is sensitive to the global consistency of the scene, which can provide some understanding of the different extent of the release from barberpole motion for the near and far depth conditions. Moveover, when multiple apertures are present, contour completion mechanisms seem to play a role in contour classification, and hence, perceived motion direction.

Throughout this paper, the extrinsic/intrinsic problem has been cast as a classification problem. It should be noted, however, that the visual system does not seem to treat terminator classification as a bipartite decision. Rather, the continuous modulation of perceived motion direction evident in Figs. 3 and 4 suggests that the visual system classifies a contour terminator along a graded continuum that spans the entire range between intrinsic and extrinsic. Some recent experiments by Shapley, Gordon, Truong, and Rubin (1995) demonstrated that contrast is another continuous dimension that the visual system uses to determine the *extent* to which contour terminators are intrinsic or extrinsic. Therefore, the term classification should be interpreted as defining the endpoints on a scale, not a rigid dichotomy.

In sum, the nature of the data seem to suggest that the extrinsic/intrinsic classification of a stereoscopic contour segment relies on both local computations that determine whether a feature is matchable or unmatchable, in addition to non-local, integrative processes that are involved in assessing the global consistency of the scene interpretation, including the completion of partially occluded figures.

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